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RADIATIVE TRANSFER IN THE ATMOSPHERES OF VENUS AND MARS

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Abstract: An approximate theory of radiative transfer in planetary atmospheres is developed and applied to atmospheres of Venus and Mars. The results for Venus indicate that the atmosphere of that planet must have an optical thickness of 60 in the infrared, corresponding to a transmission of 10^{-26}, in order to produce the observed surface temperature of 600° K. The surface temperature and tropopause height of Mars are also investigated.

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Резюме: Разработанная приближенная теория радиационного переноса в планетных атмосферах и переменена к атмосферам Марса и Венеры. Результаты для Венеры отмечают, что атмосфера этой планеты в ИК области должна иметь 60 оптическую толщину, которая соответствует пропусканию 10^{-26}, чтобы создать наблюдаемую температуру поверхности в 600°K. Также исследовались температура поверхности и высотса тропопаузы Марса.

Recent measurements of the intensity of the radiation emitted from the planet Venus in the region of centimeter wavelength show that this intensity corresponds to thermal radiation at a temperature of approximately 600 °K [1]. Since radiation in the decimeter region probably passes through the atmosphere and clouds of Venus without attenuation [2], it is usually assumed that the measured radiation intensities give the temperature of the surface of Venus.

If the albedo of Venus is taken as 0.76 [3] the surface of the planet would have an equivalent black body temperature of 230 °K.

The difference between 230 °K and the observed temperature of 600 °K is usually ascribed to a greenhouse effect, in which the infrared radiation emitted from the surface of the planet is partly absorbed by the atmosphere and reradiated to the ground.

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Sagan [4] has estimated the required degree of absorption in the atmosphere by considering the simple statement of energy balance,

$$(1-\alpha)\, T_G{}^4 = T_e{}^4 \tag{1}$$

in which α is the fraction of infrared energy absorbed in the atmosphere, T_G is the ground temperature and T_e is the effective temperature of the planet. For Venus we have $T_G = 600$ °K, and $T_e = 230$ °K for an albedo of 0.76, assuming rapid rotation of the planet.

If Venus is rotating slowly or synchronously, T_e may be as high as $\sqrt[4]{2} \times 230° = 276$ °K on the sunlit side. However, the 600 °K datum refers to the position of inferior conjunction, i.e. to the dark side of the planet. There is some indication of $T > 600$ °K on the bright side but, due to the uncertainty of the order of magnitude of the phase effect, the radio brightness temperatures on the day side of Venus are very controversial [1].

In the case of Venus rotating rapidly, we substitute the above values of T_G and T_e in eq. [1] to obtain $\alpha = 0.995$ or $e^{-\tau_0} = 0.005$ or $\tau_0 \cong 5$, where τ_0 is the total optical thickness of the atmosphere.

It is also suggested by Sagan that an atmosphere consisting of approximately two atmospheres (NTP) of CO_2 plus 10 g/cm^2 of water vapor will produce the required infrared absorption of 99.5 %.

In the above estimate of the greenhouse effect, however, the loss of energy by radiation from the top of the atmosphere is neglected, but a correction can be made for this loss by solving the equation of radiative transfer for the problem. The transfer problem is very difficult when allowance is made for the strong frequency dependence of the molecular absorption coefficients in the infrared, but for a first estimate of the magnitudes involved we will assume a grey atmosphere. We will also use the Eddington approximation, which will be an accurate approximation, in the optically dense atmosphere of Venus.

With these approximations the solution to the transfer equation is

$$T_G{}^4 = T_e{}^4 \left(1 + \tfrac{3}{4}\, \tau_0\right) \tag{2}$$

where T_G, T_e and τ_0 are defined as above. Inserting the previously given values for T_G and T_e we find that $\tau_0 \sim 60$, corresponding to a transmission of e^{-60} or 10^{-26}.

Thus, the allowance for loss of energy by radiation from the top of the atmosphere reduces the greenhouse effect by a substantial degree. In order to reach a ground temperature of 600°, the atmosphere must absorb all but 10^{-26} of the ground radiation. According to eq. (2) an absorption of 0.995

raises the ground temperature to only 340 °K. Thus the present results place much more severe requirements on the absorptive properties of the Venus atmosphere than the original estimate by Sagan.

One of us (S.I.R.) has estimated the opacity of the H_2O and CO_2 absorption bands for the concentrations suggested by Sagan, and at the high temperatures and pressures relevant to the Venus problem. The results of the calculation are shown in table 1 for a temperature of 600 °K. We find that, as Sagan has suggested, the intensification of the bands at this temperature makes all regions of the spectrum highly opaque. However, the intervals $3.5\,\mu - 4\,\mu$, $7\,\mu - 9\,\mu$, and $11.5\,\mu - 12\,\mu$ are relatively transparent in comparison with the surrounding regions, although the transmission through these "windows" is still very small.

TABLE 1

Infrared transmission.

$T = 600°$ K CO_2: 2 atm (NTP) H_2O: 10 g/cm^2

Wavelength (μ)	Transmission
2.0– 3.5	e^{-16}
3.5– 4.0	e^{-14} ←
4.0– 7.0	$< e^{-24}$
7.0– 9.0	e^{-9} ←
9.0–11.5	$< e^{-58}$
11.5–12.0	e^{-11} ←
12.0–17.0	$< e^{-22}$
17.0–20.0	$< e^{-16}$

From table 1 we find a Planck mean transmission of 10^{-5} through these "windows", from which we compute, with the aid of eq. (2), a ground temperature of 430 °K.

The absorption must therefore be recomputed at 430 °K, but at this lower temperature the windows in table 1 open up, reducing τ_0 and therefore T_G. By subsequent iterations we arrive at $\tau_0 = 3.4$, and therefore, from eq. (2), a $T_G \sim 320$ °K for this model.

Although the validity of these results is qualified by uncertainties in the extrapolation of the absorption line profiles to great distances from their centers, still they suggest that it is difficult to achieve the necessary opacity for a 600 °K ground temperature, with the quoted atmospheric model. It may also be added that Arking [5] has recently shown that in a non-grey atmosphere, which is closer to reality, the "windows" reduce the ground temperature to values lower than those estimated above for the case of grey atmospheres. This makes it still more difficult to achieve the observed high surface temperature with the assumed model atmosphere.

However, the atmospheric model used by us and Sagan may not be correct for Venus. Spinrad [6] has advanced evidence for an extremely dense Venus atmosphere, containing mostly N_2 at a surface pressure of ~ 7 atmospheres, with CO_2 present as a minor constituent in a mixing ratio of $\sim 5\ \%$. Pressure broadening and induced dipole absorption in this very dense atmosphere could provide the opacity necessary to account for the 600 °K temperature.

It should also be noted that the brightness temperature at 1 cm wavelength would be increased by as much as 50 °K over the true ground temperature, if a layer of the atmosphere existed which was at high temperature, and also absorbed, and therefore emitted in the micro-wave region. Measurements are in progress on the absorption coefficients of CO_2 and H_2O in the micro-wave region, at high pressures and temperatures for application to planetary atmosphere problems.*

The same theory of radiative transfer may be applied to Mars. The total Martian atmosphere is ~ 1800 m-atm thick, composed, presumably, of N_2, with a surface pressure of 85 mb or about 1/12 the surface pressure on the earth [7]. The only atmospheric constituent so far detected on Mars is CO_2 [8], and Goody and Grandjean [9] estimate its abundance as ~ 35 m-atm. No water vapor has been detected and the upper limit on Martian H_2O is 20 μ of precipitable water. De Vaucouleurs [7] estimates a mean surface temperature of 230 °K.

The Eddington approximation is not accurate for the solution of radiative transfer equation in this relatively thin Martian atmosphere. A more exact treatment of the transfer problem, applicable to optically thin grey atmospheres, has been developed by Arking [5] and applied to Mars. This calculation assumes a surface convective layer with an adiabatic temperature gradient of -3.7 °K/km and an effective temperature of 217 °K, which corresponds to the average solar irradiation on Mars, reduced by an albedo of 0.15. Based on a mean molecular weight of 28.3 and a mean atmospheric temperature of 200 °K the absorbing scale height was assumed to be 20 km.

The surface temperatures computed in this way are shown in fig. 1. From fig. 1 we may, as with Venus, deduce the optical thickness necessary to give the measured surface temperature. We find that the observed Martian surface temperature of 230 °K corresponds to an optical thickness of 0.40. (In the Eddington approximation it would be 0.52.) Rasool has estimated an optical thickness in the infra-red of ~ 0.2 for the specified atmospheric composition

* P. Thaddeus. Private communication.

at Martian pressures, which suggests that if the observed temperature of 230 °K is correct, some additional source of absorption is present in the Mars atmosphere, beyond the quoted amounts of CO_2 and H_2O. Also, de Vaucouleurs (private communication [10]) estimates the total integrated albedo (visible and infra-red) as 0.26 ± 0.02 instead of 0.15 as used in these

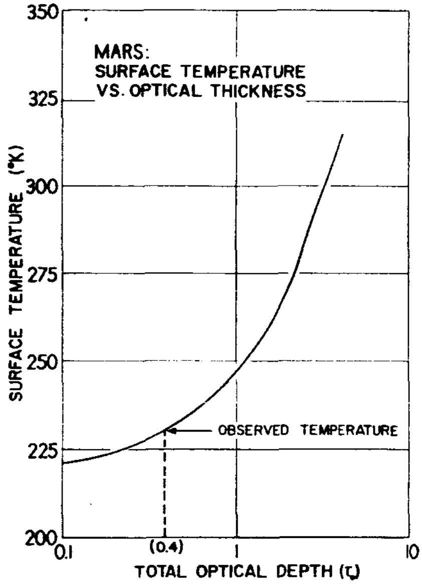

Fig. 1. Calculated surface temperatures of Mars as a function of total optical thicknesses of the atmosphere.

calculations. This would decrease the effective temperature of Mars to 210 °K, requiring a still higher opacity to raise the ground temperature to the observed value of 230 °K.

The same calculations also predict the termination of the convective layer on Mars at a height of 8 km. However this discussion of the convective layer is based on the assumption that the temperature in the lower atmosphere is determined solely by the transfer of infrared radiation emitted from the ground. In the optically thin atmosphere of Mars other sources may make a comparable or greater contribution to the thermal structure. For example O_3 formation near the ground may lead to ultraviolet heating, and raise the temperature of the lower atmosphere above the ground temperature, thus suppressing vertical convection. Assuming an oxygen content of 100 cm-atm in Mars (the upper limit on observation is 240 cm-atm) [11] a calculation of the O_3 content on Mars, by a model developed in analogy with an approximate theory of ozone formation on the earth, leads to a density between 10^{11} and 10^{12} ozone molecules/cm^3 at the ground, the concentration decreasing with altitude with a scale height of $\sim$ 15 km. A layer with this density would produce substantial heating rates in the lower atmosphere of Mars.

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